The origin of the magnetic fields of the universe: The plasma astrophysics of the free energy of the universe*

Stirling A. Colgate† and Hui Li
Theoretical Astrophysics, T6, Los Alamos National Laboratory, Los Alamos, New Mexico 87545

Vladimir Pariev
Theoretical Astrophysics, T6, Los Alamos National Laboratory, Los Alamos, New Mexico 87545; Steward Observatory, University of Arizona, 933 North Cherry Avenue, Tucson, Arizona 85721; and P. N. Lebedev Physical Institute, Leninsky Prospect 53, Moscow 11792, Russia

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The interpretation of Faraday rotation measure maps of active galactic nuclei (AGNs) within galaxy clusters has revealed ordered or coherent regions, $L_{\mathrm{mag}} \sim 50-100$ kpc ($\sim 3\times10^{23}$ cm), that are populated with large, $\sim 30\ \mu$G magnetic fields. The magnetic energy of these coherent regions is $L_{\mathrm{mag}}^3(B^2/8\pi)\sim 10^{59-60}$ ergs, and the total magnetic energy over the whole cluster ($\sim$1 Mpc across) is expected to be even larger. Understanding the origin and role of these magnetic fields is a major challenge to plasma astrophysics. A sequence of physical processes that are responsible for the production, redistribution, and dissipation of these magnetic fields is proposed. These fields are associated with single AGNs within the cluster and therefore with all galaxies during their AGN (active galactic nucleus or quasar) phase, simply because only the central supermassive black holes ($\sim 10^8 M_\odot$) formed during the AGN phase have an accessible energy of formation, $\sim 10^{61}$ ergs, that can account for the magnetic field energy budget. An $\alpha-\Omega$ dynamo process has been proposed that operates in an accretion disk around a black hole. The disk rotation naturally provides a large winding number, $\sim 10^{11}$ turns, sufficient to make both large gain and large flux. The helicity of the dynamo can be generated by the differential plume rotation derived from star-disk collisions. This helicity generation process has been demonstrated in the laboratory and the dynamo gain was simulated numerically. A liquid sodium analog of the dynamo is being built. Speculations are that the back reaction of the saturated dynamo will lead to the formation of a force-free magnetic helix, which will carry the energy and flux of the dynamo away from the accretion disk and redistribute the field within the clusters and galaxy walls. The magnetic reconnection of a small fraction of this energy logically is the source of the AGN (active galactic nucleus or quasar) luminosity, and the remainder of the field energy should then dominate the free energy of the present-day universe. The reconnection of this intergalactic field during a Hubble time is the only sufficient source of energy necessary to produce an extragalactic cosmic ray energy spectrum as observed in this galaxy, and at the same time allow this spectrum to escape to the galaxy voids faster than the GZK (blackbody radiation) loss. [DOI: 10.1063/1.1351827]

I. INTRODUCTION

The total energy released by the growth of supermassive black holes at the center of nearly every galaxy is large and can be comparable or even larger than that emitted by stars in the universe. Recent observations suggest that radiation from active galactic nuclei (AGNs or quasars) might account for only $\sim$10% of this energy.[1] Where did the rest of the energy go? We propose that a major fraction of this energy has been converted into magnetic energy and stored in the large scale magnetic fields primarily external to each galaxy, in galaxy clusters and ''walls.'' We have envisioned a sequence of key physical processes that describes this energy flow.[2,3] The proposed picture starts with the 2:1 density perturbations of the galactic mass Lyman-α clouds emerging by gravitational instability from the perturbation structure of the early universe.

The collapse of these clouds forms the galaxies. Furthermore a small, innermost fraction, $\sim 10^{-3}$, collapses via an accretion disk to form a supermassive central black hole. As the result of an immense dynamo in this accretion disk, most of the accessible energy of formation of the black hole is transformed to magnetic field, which subsequently reconnects, producing high energy particles. This field and particle energy ultimately fill the galaxy walls and the voids of the structure of the universe. A consistent explanation of this filling process requires a unique process, apparently analogous to the ''flux conversion'' of the spheromak and reverse field pinch. Hence plasma physics is central to the understanding of the flow of free energy and even structure of the universe.

Here, we present some of our recent results in under-

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†Invited speaker.

standing this sequence of phenomena. In Sec. II we summarize the observational evidence for the existence of immense magnetic fields, mostly based on Faraday rotation of AGNs in galaxy clusters and on synchrotron luminosity measurements of all radio galaxies. We briefly discuss our theoretical work on the formation of an accretion disk of the necessary mass and then how this forms the supermassive black holes in Sec. III. In Sec. IV we describe a dynamo process in this disk by including star–disk collisions, from which the necessary *helicity* for the $\alpha-\Omega$ dynamo is created. We have demonstrated this flow structure in our laboratory experiments. In Sec. V, we show results from the numerical simulations on the existence of a dynamo. The likely backreaction of this dynamo is discussed in Sec. VI, as well as our preliminary calculations on the formation of the force-free magnetic helix. In Sec. VII we consider further the distribution and possible dissipation of this magnetic energy.

II. MAGNETIC FLUX AND ENERGY IN GALAXY CLUSTERS

Recently, high quality Faraday rotation measure maps of synchrotron sources (e.g., jets from AGNs) embedded in galaxy clusters where the distances are known have become available.[4–7] (The Faraday rotation is the rotation of the plane of polarized radiation, from a background radio source, by an aligned field and a plasma electron density. This electron density is measured by x-ray emission.) An important quantity that has received less discussion previously is *the magnitude of the magnetic flux and energy* (but see Burbidge[8]). Figure 1 shows the Faraday rotation map of the region illuminated by Hydra A, the most luminous AGN in the Hydra cluster of galaxies (courtesy of Taylor and Perley[4]). The largest single region of highest field in this map has approximately the following properties: the size $L\simeq 50$ kpc (1 kpc$=3\times 10^{21}$ cm) and $B\simeq 33$ μG, derived on the basis that the field is patchy and is tangled on a 4 kpc scale. This leads to a startling estimate of flux, $F\approx BL^2\simeq 8\times 10^{4}1$ G cm^2, and energy, $W=(B^2/8\pi)L^3\simeq 4\times 10^{59}$ ergs, assuming that the field is closed on the scale of the jet and is confined only to the 50 kpc region. Measurements of field averaged throughout the whole cluster[5] indicate that it is magnetized throughout with a mean field of $\simeq 3$ μG out to a radius of $\sim$300 kpc. Then the implied flux and energy are correspondingly larger by a factor of $\sim$4, respectively. A similar conclusion can be reached when a larger sample of galaxy clusters is analyzed using the data presented in Eilek.[6] In addition this emission and strong polarization itself has strongly suggested synchrotron emission requiring even larger magnetic fields and energy.[7] It is extraordinary that Faraday rotation is seen at all and furthermore that it is so highly coherent over such large dimensions as in Fig. 1. The observation of these large coherent Faraday rotation regions requires a magnetized polarized source with no internal Faraday rotation overlaid by a magnetized screen of uniform electron density and field. To put the above-mentioned numbers in perspective, a typical galaxy like ours has a magnetic flux and energy of 10^{38} G cm^2 and 4×10^{54} ergs, respectively. (A cluster typically contains hundreds to one thousand galaxies.) The magnitude of the implied fluxes and energies in galaxy clusters are so large, $\times 10^4$ and $\times 10^{5-6}$, respectively, compared to these quantities within standard galaxies that a new source of energy and a different form of dynamo are required than that due to the motions of the galaxy itself in order to explain the origin of these magnetic fields.

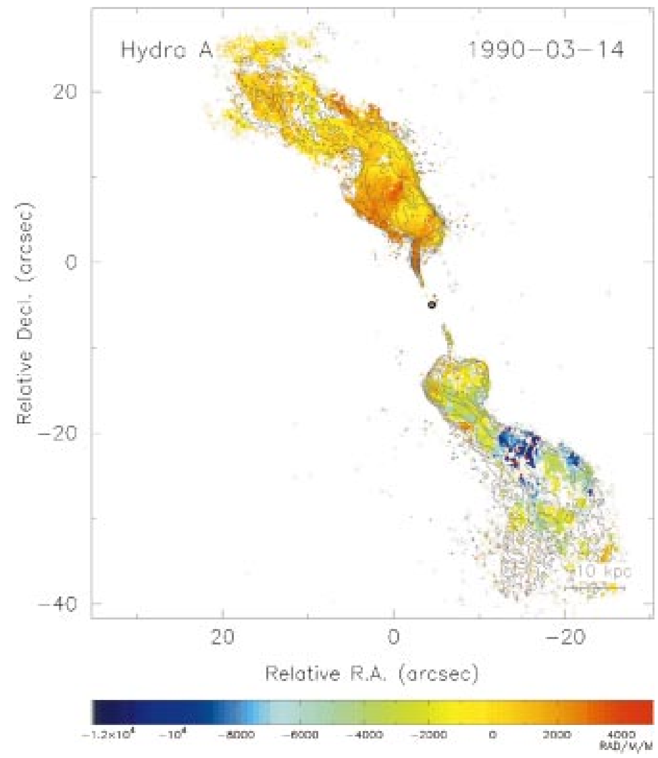

FIG. 1. (Color) The Faraday rotation measurement of Hydra A cluster. The contours indicate the synchrotron emission intensity. The field derived from the Faraday rotation is 33 μG with total energy $\simeq 10^{60}$ ergs. The minimum energy derived from the synchroton luminosity is also $\simeq 10^{60}$ ergs (Courtesy of Taylor and Perley, 1993).

A supermassive black hole in an AGN offers an attractive site for the production of these magnetic fields since the accessible energy of formation of a supermassive black hole of $\sim 10^8 M_\odot$ is $\sim 10^{61}-10^{62}$ ergs. We now discuss this possibility in detail.

III. FORMATION OF ACCRETION DISK VIA ROSSBY VORTICES

The physics of forming a supermassive black hole at galaxy centers is poorly understood; as is the formation of galaxies. It is believed that Lyman-α clouds are the first large scale, radius $\simeq 300$ kpc (10^{24} cm), nonlinear structures formed in the early universe when the density contrast exceeds 2:1. The subsequent gravitational collapse of both the dark matter and the baryonic matter has been a subject of intense research. In Fig. 2 we present a simplified view on how this collapse might proceed. The dark matter collapse is dissipationless and has been extensively simulated using numerical *N*-body codes.[9] This is represented by the black curve in Fig. 2. This collapse is inhibited by the partial conservation of the virial energy of every particle of dark matter. This results in only a small interior mass fraction at small

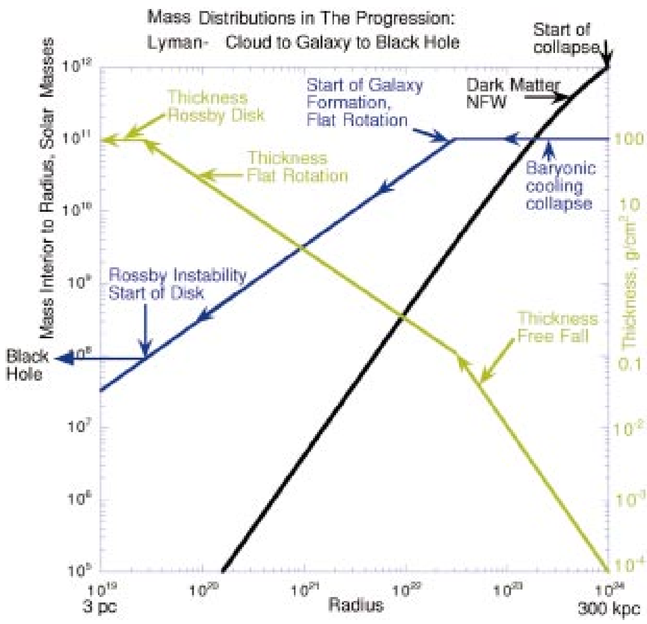

FIG. 2. (Color) A simplified description of interior mass vs radius during the collapse of a galactic mass Lyman-α cloud. The evolution of dark matter ($\sim 10^{12} M_{\odot}$) and baryonic matter ($\sim 10^{11} M_{\odot}$) are shown as the black and blue curves, respectively. The slope of the blue curve corresponds to $M_{\text{interior}} \propto R$, the mass distribution inferred from the observation of the ''flat rotation curve.'' The green curve shows how the baryonic surface density varies during the collapse (ordinate is indicated on the right-hand side). It shows that this thickness reaches the critical thickness, $\simeq 100$ g cm^{-2} for the formation of the Rossby vortex instability at $R = 10$ pc where $M_{\text{interior}} = 10^8 M_{\odot}$ all of which collapses to a massive black hole.

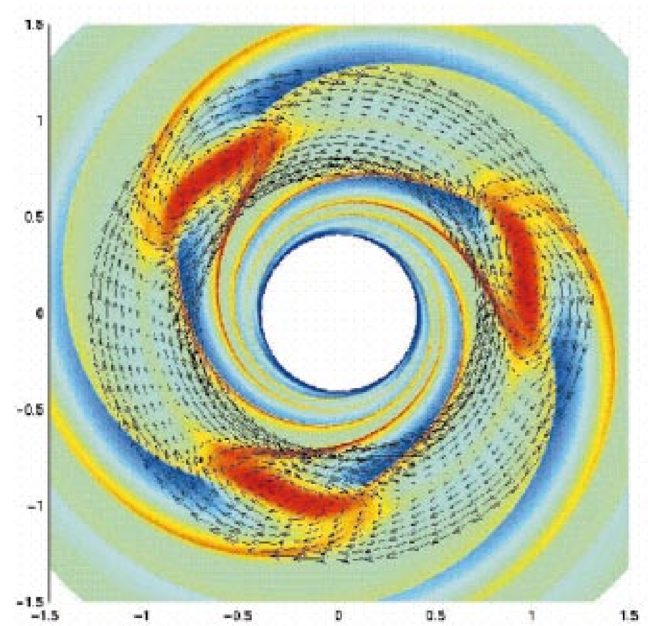

FIG. 3. (Color) A two-dimensional simulation of the formation of the Rossby vortex instability in a Keplerian disk with an initial radial pressure gradient of $\Delta P/P = 0.5$. These vortices transmit angular momentum with both a linear as well as nonlinear amplitude.

radii. The baryonic matter, on the other hand, shown as the blue curve in Fig. 2, collapses differently because the molecular collision cross section is so large that the gas cannot interpenetrate itself like dark matter (cloud surface density $\simeq 10^{-4}$ g cm^{-2}), and so becomes shock heated and cools by radiation. After the initial (essentially) free-fall collapse with small (conserved) angular momentum, a rotating spheroid is formed with a partial Keplerian (rotation) support. Hence the baryonic collapse to this point depends critically upon the initial angular momentum of the Lyman-α cloud characterized by a parameter $\lambda \simeq v_{\text{cloud}}/v_{\text{Keplerian,cloud}}$ averaged over the cloud. Both theoretical estimates by Peebles[10] and the numerical calculations by Warren *et al.*[11] give $0.05 < \lambda < 0.07$ with a wide dispersion. Hence, the cloud is only slowly rotating slowly. As the cloud collapses this rotation speeds up because of the conservation of angular momentum, eventually reaching the condition of partial centrifugal or Keplerian support. The radius of partial Keplerian support occurs where one expects the onset of the McClauren spheroid instabilities or where $\lambda_{\text{spheroid}} \simeq 0.4$. Since $v_{\text{Keplerian,spheroid}} \propto v_{\text{Keplerian,cloud}} (R_{\text{cloud}}/R_{\text{spheroid}})^{1/2}$, then $R_{\text{spheroid}} \simeq (\lambda_{\text{cloud}}/\lambda_{\text{spheroid}})^2 R_{\text{cloud}}$. This parameter determines the start of a galaxy structure and in particular determines the constant rotation velocity distribution (i.e., the ''flat'' rotation curve characteristic of all spiral galaxies). This constancy of rotational velocity implies that the total baryonic mass M_{interior} inside a certain radius R scales as $M_{\text{interior}} = M_{\text{spheroid}}(R/R_{\text{spheroid}})$, the blue curve in Fig. 2. In Fig. 2, we have also plotted the baryonic surface density Σ (gm cm^{-2}), the green curve. The surface density is an important quantity since it directly determines whether the disk is ''thick'' enough to contain its heat against radiative cooling. In other words, only when the disk exceeds a certain critical thickness Σ_c could the hydrodynamic structures within the disk survive long enough to play a role in angular momentum transport. Based on the opacity estimates, this critical surface density is $\Sigma_c \simeq 100$ g cm^{-2}. The green curve in Fig. 2 shows the increase of Σ from the initial Lyman-α cloud value 10^{-4} g cm^{-2} to eventually Σ_c in several baryonic collapse phases. Two interesting quantities emerge from this simple scaling: $\Sigma_{\text{spheroid}} \simeq (0.4/\lambda_{\text{cloud}})^4 \Sigma_{\text{cloud}} \simeq 0.1$ g cm^{-2} is at the start of the flat rotation curve so that the radius when $\Sigma_{\text{flat}} \approx \Sigma_c$ is ~ 10 pc and the total baryonic mass inside this scale is $M_{\text{disk}} \simeq \Sigma_c \pi R^2 \simeq \Sigma_c/\Sigma_{\text{spheroid}} \simeq 10^8 M_{\odot}$. We associate this size to be the accretion disk size and the mass to be the mass of the central black hole. One key step in allowing the formation of the central black hole described previously is to find a mechanism to explain the radially outward transport of angular momentum. We have identified one plausible process, namely the Rossby vortex mechanism.[12,13] We have found a global nonaxisymmetric instability in thin disks that can excite large scale vortices in the disk. Such vortices are shown to transport angular momentum outward efficiently.[14] A numerical simulation showing the production of vortices is shown in Fig. 3. A sufficient condition for the initiation of the Rossby vortex instability (RVI) is a radial pressure gradient where $\Delta P/P \sim > 0.1$ such as would be created by the continuing feeding of mass as creates the ''flat rotation curve.'' This mass distribution where $M_{\text{interior}} \propto R$ results in a thickness $\Sigma \propto 1/R$, the green curve in Fig. 2. Because of the torque transmitted by the vortices, all of the disk mass is then accreted to a black hole mass of $\sim 10^8 M_{\odot}$. This mass in turn

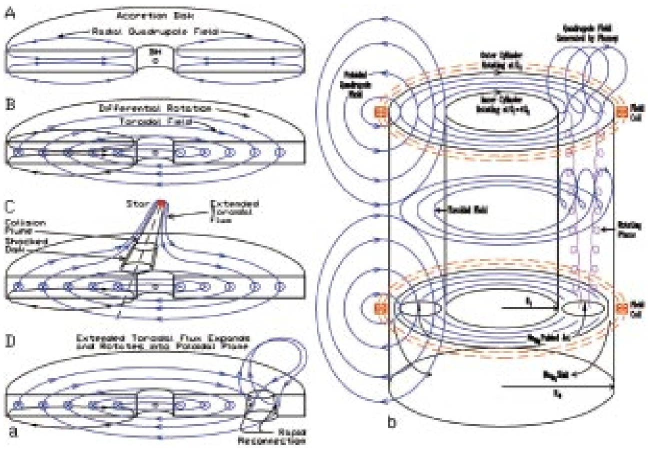

FIG. 4. (Color) (a) A schematic drawing of an $\alpha-\Omega$ dynamo in an accretion disk. The initial quadrupole poloidal field (A) is sheared by the differential rotation in the disk, developing a strong toroidal component (B). As a star passes through the disk, it shock heats the matter of the disk and lifts up a fraction of the toroidal flux and produces an expanding plume (C). After the plume and loop of flux is rotated by $\sim\pi/2$ rad, reconnection is invoked to merge the new poloidal flux with the original flux (D). (b) A liquid sodium dynamo experiment, mimicking the accretion disk dynamo. The conducting fluid between the two cylinders is rotated differentially (Couette flow), shearing the radial component of an external quadrupole field into a toroidal field. Plumes are driven off-axis, resembling the star–disk collisions. The resistivity of the fluid ensures the reconnection.

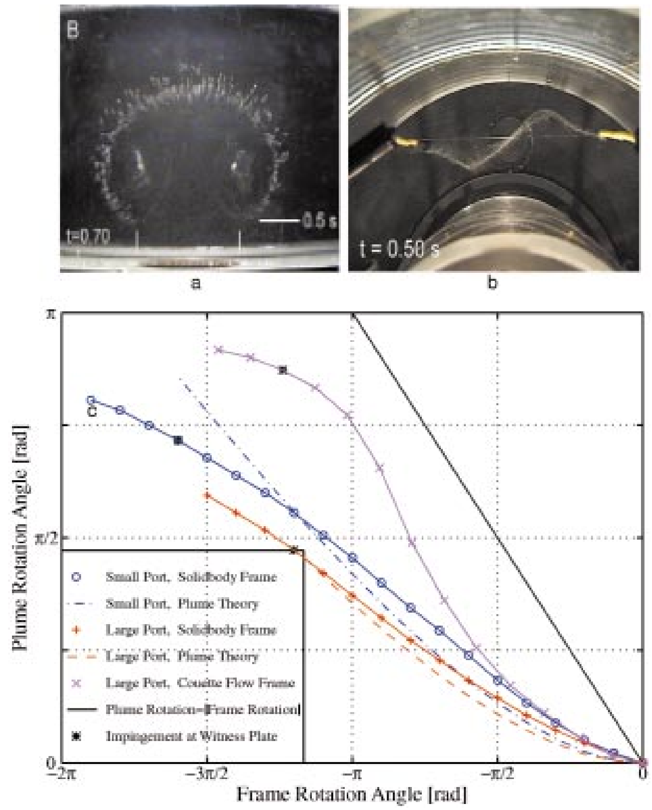

FIG. 5. (Color) The plume rotation experiment (Ref. 14). (a) Viewed from the side: A plume is driven upwards and expands. Bubbles outline the boundary of the plume. (b) Viewed from above in a co-rotating frame: The rising plume rotates or twists relative to the frame, creating a coherent, large scale helicity. (Bottom) The measurements of the relative rotation are compared to theory.

defines the accessible free energy available through the dynamo to produce these immense magnetic fields.

IV. THE $\alpha-\Omega$ DYNAMO IN THE BLACK HOLE ACCRETION DISK

An accretion disk is an attractive site for the dynamo since it has Keplerian differential rotation and nearly $\simeq 10^{11}$ revolutions close to the black hole during its formation time of $\sim 10^8$ years. The key ingredient in our proposed $\alpha-\Omega$ dynamo is the star–disk collisions that provide the helicity generation process for the dynamo.[2,15] We envision a physical sequence for the dynamo that is shown in Fig. 4. Figure 4(a) shows an initial quadrupole magnetic field within a conducting accretion disk. The Keplerian differential rotation within the conducting accretion disk wraps the radial component of the quadrupole field into a much stronger toroidal field, Fig. 4(b). This is the Ω deformation. A plume, driven by a star–disk collision, carries a fraction of this now multiplied toroidal flux above the surface of the disk, Fig. 4(c). Figure 4(d) shows that as the plume expands into the near vacuum away from the disk, the plume rotates differentially, always in the same direction, relative to the rotating frame. This rotation carries and twists (counter-rotates) the loop of toroidal flux, $\sim\pi/2$ rad, into the orthogonal, poloidal plane. This is the α deformation, or *helicity* of the dynamo process. Reconnection allows this loop of flux to merge with the original quadrupole flux, thereby augmenting the initial quadrupole field. For positive dynamo gain, the rate of adding these increments of poloidal flux must exceed the negative quadrupole resistive decay rate. These same large-scale plumes driven by convection in a star with internal differential rotation should similarly produce a dynamo. In the right panel of Fig. 4, we also show the schematic of a liquid sodium experiment we are developing that simulates the astrophysical dynamo in the laboratory. In this case the magnetic Reynolds number of the sodium Couette flow is $R_{m,\mathrm{Couette}} \simeq 130$ and for the plumes $R_{m,\mathrm{plumes}} \simeq 15$ as compared to much larger values for the accretion disk. For positive dynamo gain, the rate of addition of poloidal flux must be greater than its decay. It is only because the toroidal multiplication can be so large (or that $R_{m,\Omega}$ can be so large) that the generation of helicity in this $\alpha-\Omega$ dynamo can be more rare and episodic. This is different from the α^2 dynamos of Rädler and Gailitis.[16,17] Key to both the astrophysical accretion disk dynamo and the laboratory experiment is this new source of helicity produced coherently on the large scale by plumes driven off axis in a rotating frame. We have demonstrated how this plume rotates in a water analog flow visualization experiment. An expanding plume partially conserves its own angular momentum so that the change in moment of inertia causes a differential rotation. Figure 5 shows this rotation effect.

V. KINEMATIC DYNAMO SIMULATIONS

We have performed kinematic dynamo calculations using a three-dimensional code calculating time evolution of the vector potential of the magnetic field by a time-dependent velocity flow field. We use the vector potential, because $\nabla\cdot\mathbf{B}$ remains zero at all times and no periodic calculational ''cleaning'' of $\nabla\cdot\mathbf{B}$ has to be performed. The boundary condition is perfectly conducting so that the flux through the boundary must be constant in time. This allows for an initial poloidal bias field, but thereafter the flux through the boundary must remain constant. Therefore all the flux generated by a dynamo must remain within the box. Since this is not the case for either the experiment or the astrophysical circumstance, we must simulate problems with the walls as far removed from the region of action as possible. A nonconducting boundary condition requires the solution of the external potential field at each time step and is planned for the future. Suppose that ϕ and $\mathbf{A}$ are the scalar potential of the electric field and vector potential of the magnetic field, such that $\mathbf{B}=\nabla\times\mathbf{A}$, $\mathbf{v}$ is the velocity field, η is the magnetic diffusivity ($\eta\approx 1/R_m$), c is the speed of light. We use the following gauge condition in our code:

$$c\varphi-\mathbf{v}\cdot\mathbf{A}+\eta\nabla\cdot\mathbf{A}=0.$$

Then, one can derive the equation for the evolution of $\mathbf{A}$,

$$\frac{\partial\mathbf{A}}{\partial t}=-A^k\frac{\partial v^k}{\partial x^i}-(\mathbf{v}\nabla)\mathbf{A}+\eta\nabla^2\mathbf{A}+(\nabla\cdot\mathbf{A})\nabla\eta.$$

The resulting magnetic field is obtained by taking curl of $\mathbf{A}$ at the last time step. The velocity field is specified to resemble the actual flow field with no $J\times B$ force or ''back reaction.'' We observe convergence for the growth rate of the dynamo and for the structure of the growing magnetic field at a grid size of $31\times 61\times 61$, which are the number of grid points in radial, azimuthal, and vertical directions, respectively. We have simulated two problems, the laboratory sodium dynamo experiment and the astrophysical accretion disk. For both problems we have observed dynamo gain either in the astrophysical case within the effective numerical diffusion limit of the code, $R_m\simeq 200$, or in the experimental case for values of $R_m\simeq 120$ and plume frequency within the experimental limits of ~ 5 Hz. We show in Fig. 6 the experimental simulation. The conditions for gain at R_m as small as in the planned experiment are more demanding than the disk where R_m is presumed to be $R_m\gg 100$.

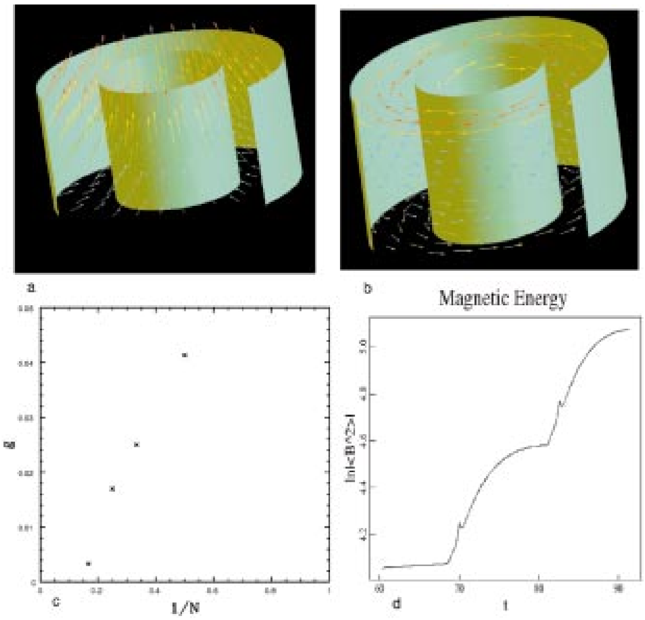

FIG. 6. (Color) The kinematic dynamo calculation. (a) An initial bias poloidal field with its radial and axial components. (b) This field is wrapped up by the differential rotation, developing a toroidal component. (c) The dynamo gain as a function of $1/N$, where N is number of revolutions during which a pair of plumes are injected. A marginal positive gain is obtained when a pair of plumes are injected every four revolutions. (d) The exponentiating field energy for $N=3$. The pulsed increase in field energy is due to the injection of each pair of plumes.

VI. FORMATION OF A FORCE-FREE HELIX

We now discuss what happens when the dynamo saturates. By definition, a dynamo has positive gain of the magnetic field in the conversion of mechanical energy into magnetic energy. Thus we expect a magnetic field, starting from an arbitrarily small ''seed'' field, to exponentiate until the linear assumptions break down, due to backreaction, and saturation occurs. This backreaction in the case of any dynamo is the ponderomotive force of the field acting on the hydrodynamic conducting fluid flows that made the dynamo action in the first place. For the α–Ω dynamo the two particular flows are the Keplerian flow of rotation, the Ω flow, and the flow producing the helicity, the α flow. We suggest that the α flow is produced by star disk collisions, where the stars are an original small mass fraction of the original Lyman-α cloud, $\sim 10^{-3}$ as is determined by absorption spectra of such clouds. The resulting plumes with trapped flux, produced by the shock interaction of the star at Keplerian velocity with the disk, are less sensitive to the ponderamotive forces of the magnetic field as compared to other possible sources of helicity, e.g., turbulence. Furthermore we expect the plume pressure to be larger than the pressure in the disk and still larger than the toroidal component of the field necessary to affect the Keplerian motion of the disk, e.g., an accretion $\alpha\simeq 0.1$. Therefore the backreaction of the dynamo acts on the Keplerian flow, which is equivalent to removing its angular momentum by doing work on the field. Thus despite the relatively low density of the disk, the backreaction causes all the kinetic energy of the disk, and thus of accretion, to be converted into magnetic energy by a ''Ω-saturated'' dynamo.

The increase of magnetic pressure in and above the disk and the strong differential rotation of poloidal fields connecting different parts of the disk can lead to the efficient expansion of the fields, away from the disk. A poloidal flux line connected at two different radii will undergo differential rotation leading to a large winding number, $N_{\text{turns}}\sim 10^{10}$ turns during the 10^8 years of formation. For a given value of B_{poloidal} external to the disk and consequently a poloidal flux, $F_{\text{poloidal}}\simeq R^2 B_{\text{poloidal}}$ and with the assumption of a conducting medium, the toroidal flux will be increased to $F_{\text{toroidal}}\simeq R^2 B_{\text{poloidal}}\times N_{\text{turns}}$. Thus for even modest values of winding, $B_{\text{toroidal}}\gg B_{\text{poloidal}}$ and at minimum energy where $B_\phi\simeq B_z$ then $B_z/B_R\gg 1$ and the centrifugal force on plasma on the field lines becomes negligible compared to the vertical component of gravity. The matter will fall back along these field lines similar to solar arcades, but with the gravitational potential $\times 10^{4-7}$ greater and for kT of the plasma ~ 100 eV. The residual plasma is that necessary to carry the current supported by a small electric field of charge separation, $E_{\mathrm{gravity}} \leqslant c^4 m_p/(2eGM_{BH}) \simeq 10^{-4}$ V/cm.

This very large toroidal flux is not likely to be confined and instead will expand to a minimum energy state leading to a force-free helix. Since the expanding fields are ''stressed/twisted,'' they also carry away energy and angular momentum from the disk (i.e., Poynting flux). Thus, the gravitational energy is released via accretion and meanwhile is being carried away by the magnetic fields, i.e., the back-reaction of the dynamo. The rate at which the magnetic energy is carried away from the disk in this case of Ω quenching is $(B^2/8\pi)(\pi R^2)v_{\mathrm{Keplerian}} = (1 M_\odot/\mathrm{yr})c^2/6 \simeq 10^{46}$ ergs/s. For $\langle R \rangle \approx 10 \times 2GM_{BH}/c^2 = 2 \times 10^{14}$ cm, the mean magnetic field is $\langle B \rangle \simeq 2 \times 10^4$ G. The current necessary to bound this field is $I = 5RB = 1.5 \times 10^{19}$ A. The density of current carriers required to carry this current is ~ 3 electrons cm^{-3} at $c/3$. All other matter will fall back toward the black hole. Such a plasma density and this field corresponds to a $\beta n_e kT/(B^2/8\pi) \simeq 10^{-14}$, implying that force free is a good description of the physical condition as the fields expand away.

We have performed preliminary calculations to simulate such an expansion process. We treat the disk as an infinitely conducting and massive boundary. The poloidal fields connecting different parts of the disk are established in a conducting medium above the disk. Then the disk starts to rotate differentially (i.e., Keplerian). The calculations are done by solving the Grad–Shafranov equation assuming axisymmetry and in steady state. We consider the force-free limit since both gravity and gas pressure are expected to play very minor roles. We use the winding number of each field line as the input control parameter, which should be conserved if there is no magnetic reconnection. Due to the nature of Keplerian rotation ($\Omega \propto R^{-3/2}$), nearly all the turns are added to the field lines connected to the innermost part of the accretion disk. These field lines will also expand axially the furthest. This is illustrated in Fig. 7.

We further speculate that the axial extension of the helix, formed by the winding of the innermost footpoints, could become a sequence of force-free, quasistatic equilibria of minimum energy, or Taylor states.[18] This, however, remains to be shown.

VII. DISTRIBUTION AND DISSIPATION OF MAGNETIC FLUX AND ENERGY

There is, however, a critical problem in understanding how the helix would expand radially, in addition to its axial expansion. The outer radial boundary of the helix is the pressure of the conducting interstellar or intergalactic medium (ISM/IGM). The magnetic pressure is likely to exceed greatly that of the ambient medium so that we expect the helix to expand radially just as it progresses axially related to the Keplerian speed of its footpoints. The radial expansion of the fields from the kilogauss level at which they are generated to the μG levels of the IGM represents a major problem

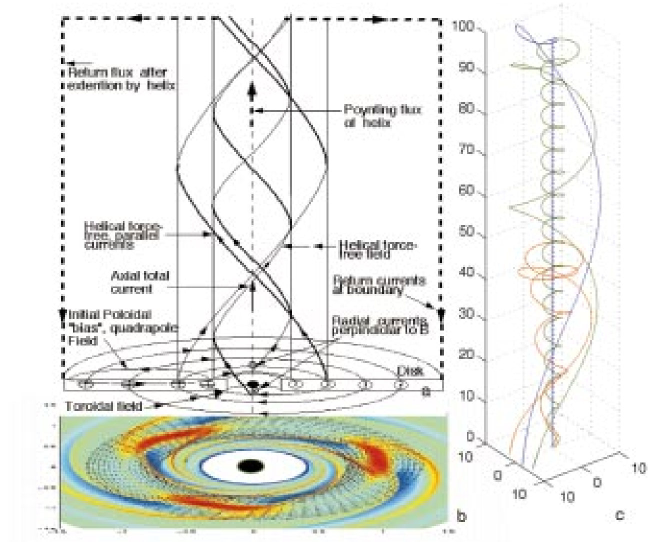

FIG. 7. (Color) The helix generated by the dynamo in the disk. The footprints of the external quadrupole field lines (a) generated by the dynamo, are attached to the surface of the disk (b). In the conducting low density plasma, $\beta \ll 1$, these field lines are wrapped into a force free helix. This helix extends from the disk carrying flux and energy, a Poynting flux, calculated with the Grad–Shafranoff equation (c).

if the poloidal (B_z) and toroidal (B_ϕ) fluxes are conserved separately. Not only will the force-free minimum energy state, the Taylor state, be destroyed, but conceptually this expansion takes place at the expense of $\int P\, dV$ work by the field. If this were to be the case, then the remaining energy in the field would be negligible after an expansion in spatial scale by the ratio of $\times 10^{10}$ (i.e., going from the size of a black hole $\sim 10^{14}$ cm to 100 kpc $\sim 3 \times 10^{23}$ cm). Consequently, all the above theories of black hole accretion disk dynamo would not be applicable. Fortunately this problem may have been solved unexpectedly by the equally unexpected behavior of the reverse field pinch, RFP, and the magnetic fields in the spheromak in the laboratory. The reverse field is the reversal of the B_z component of a cylindrically symmetric field as a function of radius. One notes exactly this reversal of the B_z flux in the helix picture of Fig. 7. The experiments show that if the outer boundary is expanded, or equivalently B_ϕ flux is added, a tearing mode reconnection takes place that generates B_z flux, partially conserves B_ϕ flux, and does this remarkable process with negligible loss of magnetic energy. The generation of B_z flux at the expense of B_ϕ energy is called a reverse field ''dynamo,'' although no mechanical energy is converted to magnetic energy. We speculate that this process allows the force-free helix to distribute its flux throughout the universe with only a very small loss of energy. The flux generated by the BH accretion disk dynamo is $F_{\mathrm{total}} = (\pi R)v_\phi B_\phi t \simeq 10^{44}$ G cm^2. Thus we feel that the black hole accretion disk dynamo can produce and distribute the necessary flux in the universe.

Finally we note that the small fractional dissipation, $\sim 5\%$–10% expected in the reconnection of the RFP helix, fulfills the necessary energy source for the AGN phenomena. The reconnection of the force free field is the dissipation of

$J_\parallel$ by $J_\parallel E_\parallel$. The run-away acceleration of electrons and ions by $E_\parallel$ proceeds until the acceleration of each is limited by its radiative losses. This acceleration limiting radiation could produce the extraordinary spectra of AGNs and quasars.[2] In conclusion we note that if even 10^{-3} of this magnetic energy fills intergalactic space for each galaxy formed, then the pressure of the field acting upon the baryonic plasma will affect the subsequent adjacent galaxy formation since the energy released is $\times 10^3$ the virialized precollapse baryonic energy. Thus, magnetic fields may play an important role in galaxy formation as well.

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[1] D. O. Richstone, E. A. Ajhar, R. Bender *et al.*, Nature (London) **395**, 14 (1998).
[2] S. A. Colgate and H. Li, Astrophys. Space Sci. **264**, 357 (1999).
[3] S. A. Colgate and H. Li, IAUS 195, ASP Conference Series 334, edited by P. C. H. Martens and S. Tsurta, 1999, unpublished.
[4] G. B. Taylor and R. A. Perley, Astrophys. J. **416**, 554 (1993).
[5] T. E. Clarke, P. P. Kronberg, and H. Böhringer, Astrophys. J. Lett. (in press).
[6] J. A. Eilek, F. N. Owen, and Q. Wang, submitted to Astrophys. J.
[7] P. P. Kronberg, Prog. Phys. **57**, 325 (1994).
[8] G. R. Burbidge, Astrophys. J. **124**, 416 (1956).
[9] J. F. Navarro, C. S. Frenk, and S. D. M. White, Astrophys. J. **490**, 49 (1997).
[10] P. J. E. Peebles, Astrophys. J. **155**, 393 (1969).
[11] M. S. Warren, P. J. Quinn, J. K. Salmon, and W. H. Zurek, Astrophys. J. **399**, 405 (1992).
[12] R. V. E. Lovelace, H. Li, S. A. Colgate, and A. F. Nelson, Astrophys. J. **513**, 805 (1999).
[13] H. Li, J. M. Finn, R. V. E. Lovelace, and S. A. Colgate, Astrophys. J. **533**, 1023 (2000).
[14] H. Li, S. A. Colgate, B. Wendroff, and R. Liska, Astrophys. J. (in press).
[15] H. F. Beckley, S. A. Colgate, V. D. Romero, and R. Ferrel, submitted to Phys. Fluids.
[16] K.-H. Rl̈er, M. Epstein, and M. Schüler, Stud. Geophys. Geod. **42**, 1 (1988).
[17] A. Gailitis, O. Lilausis, S. Demen'ev *et al.*, Phys. Rev. Lett. **84**, 4365 (2000).
[18] J. B. Taylor, Rev. Mod. Phys. **58**, 741 (1986).